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Conversion of Radio-Frequency Pulses to Continuous-Wave Sinusoids by Fast Switching and Narrowband Filtering

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14. ABSTRACT

The authors seek to reduce self-generated distortion in the transmitted probe of an intermodulation radar by applying Linearization by Time-Multiplexed Spectrum (LITMUS). In this technical note, an experiment is conducted to select a minimum time-multiplexing rate and an appropriate filter to accomplish LITMUS when transmitting cellular-band frequencies. This research will be followed by a wireless experiment that demonstrates an improvement in the linearity of a short-range intermodulation radar.

15. SUBJECT TERMS

distortion, filter, intermodulation, linearization, radar, radio frequency, self-generated, time multiplexing, transmitter

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1. Introduction

One challenge of designing a nonlinear radar is to achieve linearity in the transmitter that is high enough to detect targets whose reflections are typically very weak. The generation of a detectable nonlinear target response at a practical standoff range generally requires transmission of at least 30 dBm of average radio frequency (RF) power.[1] At the target, the loss incurred by the conversion of incident power at a set of transmit frequencies into reflected power at a different set of received frequencies and is often greater than 30 dB.[2] Therefore, the radar receiver's sensitivity must be relatively high to detect a nonlinear target.

Generating high power for transmission is achieved at the cost of linearity. At the output of a typical RF amplifier, for every 1 dB of additional peak power transmitted at the pair of frequencies, f_1 and f_2 , the power at the (undesired, spurious) third-order intermodulation frequencies, $2f_1 - f_2$ and $2f_2 - f_1$ increases by 3 dB.[3] If these self-generated spurious frequencies are not attenuated or otherwise eliminated before they arrive at the transmit antenna they will, a) couple directly from the transmitter to the receiver, or b) radiate into the environment and reflect from purely linear targets and/or clutter. Coupling from a high-power transmitter to a sensitive receiver tends to saturate the receiver such that no targets may be detected. Nonlinear reflections from linear targets and clutter manifest as false-alarm detections.

An intermodulation radar relies on the target to respond at one or more frequencies produced by the mixing of transmit frequencies that are simultaneously present in the target.[4–7] The same nonlinear electrical properties that produce harmonics at integer multiples of a single transmit frequency produce intermodulation frequencies at integer sums and differences of multiple transmit frequencies (e.g., $3f_2 - 2f_1$, $3f_1 - 2f_2$). Since these multiple transmit frequencies are usually closely spaced (i.e., because many antennas are designed to operate within a particular communications band), intermodulation frequencies are also closely spaced and appear very near to the original transmit frequencies. Filtering is rarely implemented to eliminate self-generated intermodulation as such filters must be very narrow and are thus prohibitively lossy. Common techniques used to improve linearity (i.e., linearize) in this case are predistortion[8] and feed-forward cancellation.[9]

Another distortion-mitigation technique, yet to be implemented as part of a nonlinear radar, is Linearization by Time-Multiplexed Spectrum (LITMUS).[10] The LITMUS technique reduces distortion introduced by a nonlinear element in an RF front-end (i.e., a power amplifier) by time-multiplexing an otherwise frequency-or

phase-multiplexed signal before the nonlinear element, passing the time-multiplexed version of the signal through the nonlinear element (at a lower peak power, but at the same total power as the non-multiplexed version), and reversing the time-multiplexing operation by attaching a carefully selected filter to the output of the nonlinear element. Linearity is improved at the cost of a slight increase in complexity in the RF chain and a spreading of the transmit signal's bandwidth immediately before the signal encounters the nonlinear element. In previous work, a reduction by 14 dB in third-order intermodulation was demonstrated for the generation of 4 mW of average power in 4 tones by an RF amplifier.[11] In this technical note, an appropriate filter and a minimum time-multiplexing rate are selected to apply LITMUS to intermodulation radar.[12]

2.   Experiment

To apply LITMUS to the transmission of multiple evenly spaced equal-amplitude frequencies (that will ultimately be used to illuminate a nonlinear target simultaneously), 2 subsystems of the RF chain are paramount: a) the time-multiplexer, which is illustrated in Fig. 1 as a rotary switch; and b) the filter, which is labeled in Fig. 1 as "BPF" for bandpass filter. As explained in Mazzaro et al.,[12] the time-multiplexer must be able to chip the signal spectrum at a rate that is significantly greater than the bandwidth of the filter. Also, the filter must have a passband whose width is smaller than the chip rate, and it must have a stopband that eliminates (or significantly attenuates) all spectral products introduced by the time-multiplexer.
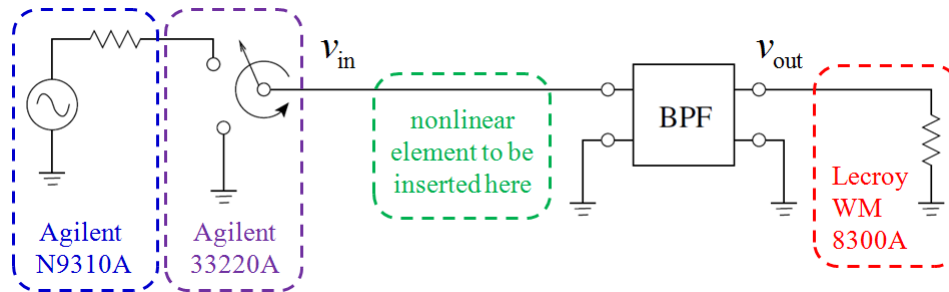
Fig. 1   Switch-and-filter experiment: equipment and arrangement

An experiment was designed to convert a single-tone RF pulse with a carrier frequency in the vicinity of 900 MHz[1] into a constant-amplitude (i.e., "always on" or "continuous") sinusoid at that same carrier frequency. The same process that converts an RF pulse into a sinusoid will convert a switched-tone signal containing multiple frequencies into a steady multitone signal.[11] Thus, a switching rate and a filter that achieve the conversion for one frequency can be used as the initial design

parameters of a wireless experiment to demonstrate the application of LITMUS to an intermodulation radar that transmits multiple frequencies.

For the experiment, a constant-envelope (3 dBm) single-frequency sinusoid is generated by the Agilent N9310A RF signal generator. Time-multiplexing is achieved by enabling in-phase/quadrature (I/Q) modulation on the N9310A and routing 1-V/0-V 50% duty-cycle pulses from the Agilent 33220A function generator to the in-phase port on the N9310A. (The quadrature port was grounded.) Essentially, the on/off signal provided by the 33220A modulated the carrier that was provided by the N9310A. The resulting RF pulses output from the N9310A were sent directly to a bandpass filter. In the follow-on experiment, the RF pulses will be sent through an amplifier (i.e., the "nonlinear element" in Fig. 1) to generate a high-power/high-linearity radar probe.[12]

The following bandpass filters were tested: MiniCircuits ZX75BP-942+ and MiniCircuits ZVBP-909+. The following carrier frequencies were tested: $f_0 = 900$ MHz to 920 MHz in 1-MHz steps. These center frequencies were chosen to stay within the passband of both filters, as required by LITMUS.[12] The following switching frequencies were tested: $f_s = 5$ MHz, 10 MHz, 20 MHz. These switching frequencies represent 3 of the highest time-multiplexing rates possible with the 33220A. The input to and output from each bandpass filter, for all frequency combinations, was captured by the Lecroy Wavemaster 8300A digitizing oscilloscope at 10 GSa/s. Figures 2–7 contain samples of the recorded data.

Figure 2 shows v_{in} and v_{out} from the 2 filters for $f_0 = 908$ MHz and $f_s = 5$ MHz. As observed, the switching frequency is sufficient to change the shape of the RF pulse as it propagates through the ZVBP-909; however, it is not high enough to change the shape of the RF pulse as it propagates through the ZX75BP-942. The shaping (or lack thereof) of the RF pulse from v_{in} to v_{out} may also be viewed in the frequency domain. Power spectra are provided in Fig. 3: P_{in} is average power corresponding to the voltage v_{in} delivered into a 50-Ω impedance; each P_{out} corresponds to each v_{out}. The closer a power spectrum resembles a single peak in the frequency domain, the closer the waveform resembles a sinusoid in the time domain. The ZVBP-909 filters the wide spectrum of the sharp RF pulse into a small subset (i.e., essentially 5) of its original Fourier components. The passband of the ZX75BP-942 is too wide to have a significant effect on the RF pulse; its P_{out} is nearly the same as P_{in}. (S-parameters for the 2 filters are provided in the Appendix.)
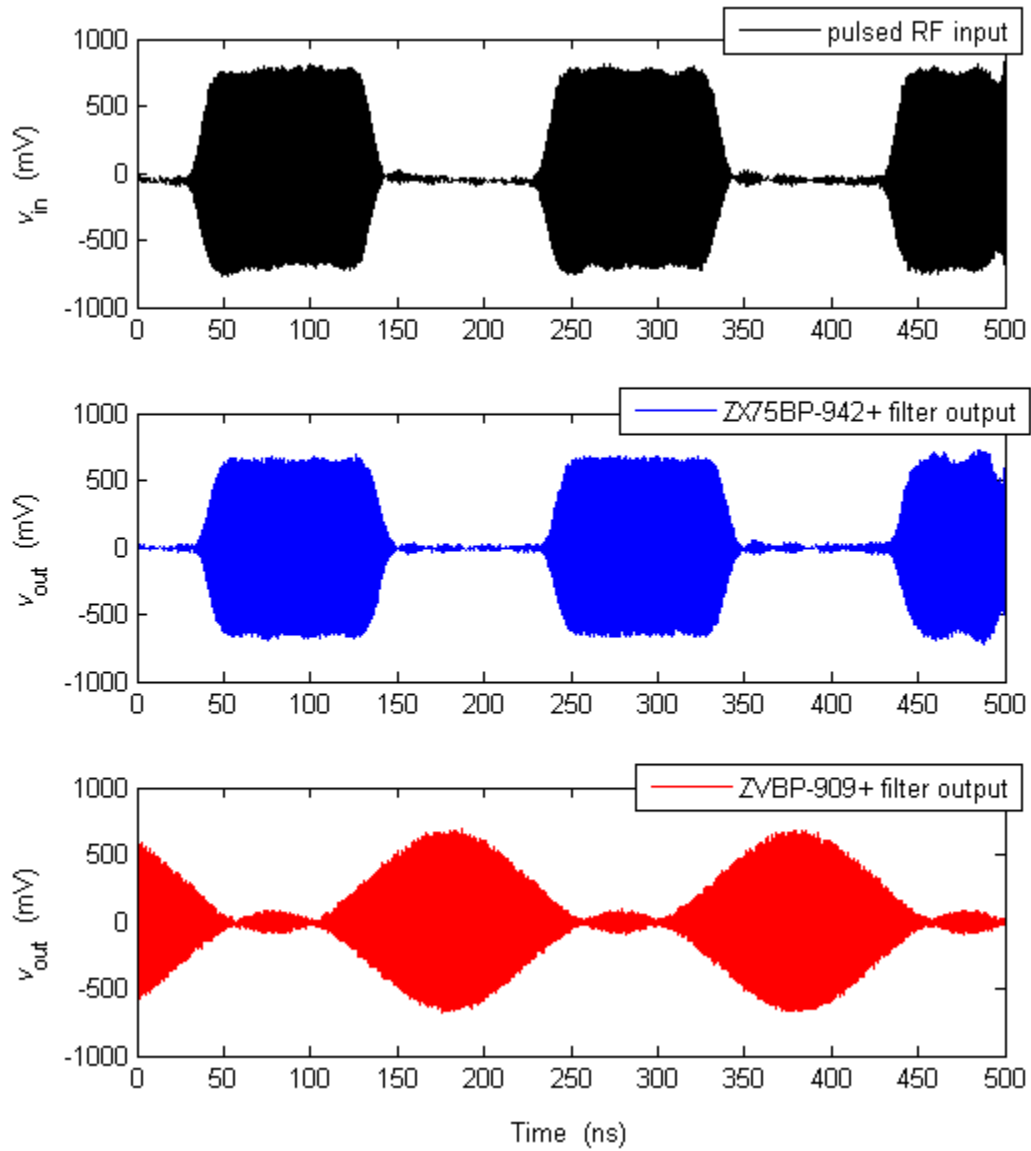
Fig. 2 **Switch-and-filter experiment: time-domain data for f_0 = 908 MHz, f_s = 5 MHz. The output of the ZX75BP-942 filter is essentially the same as the RF pulse input. The output of the ZVBP-909 filter contains significant amplitude modulation.**
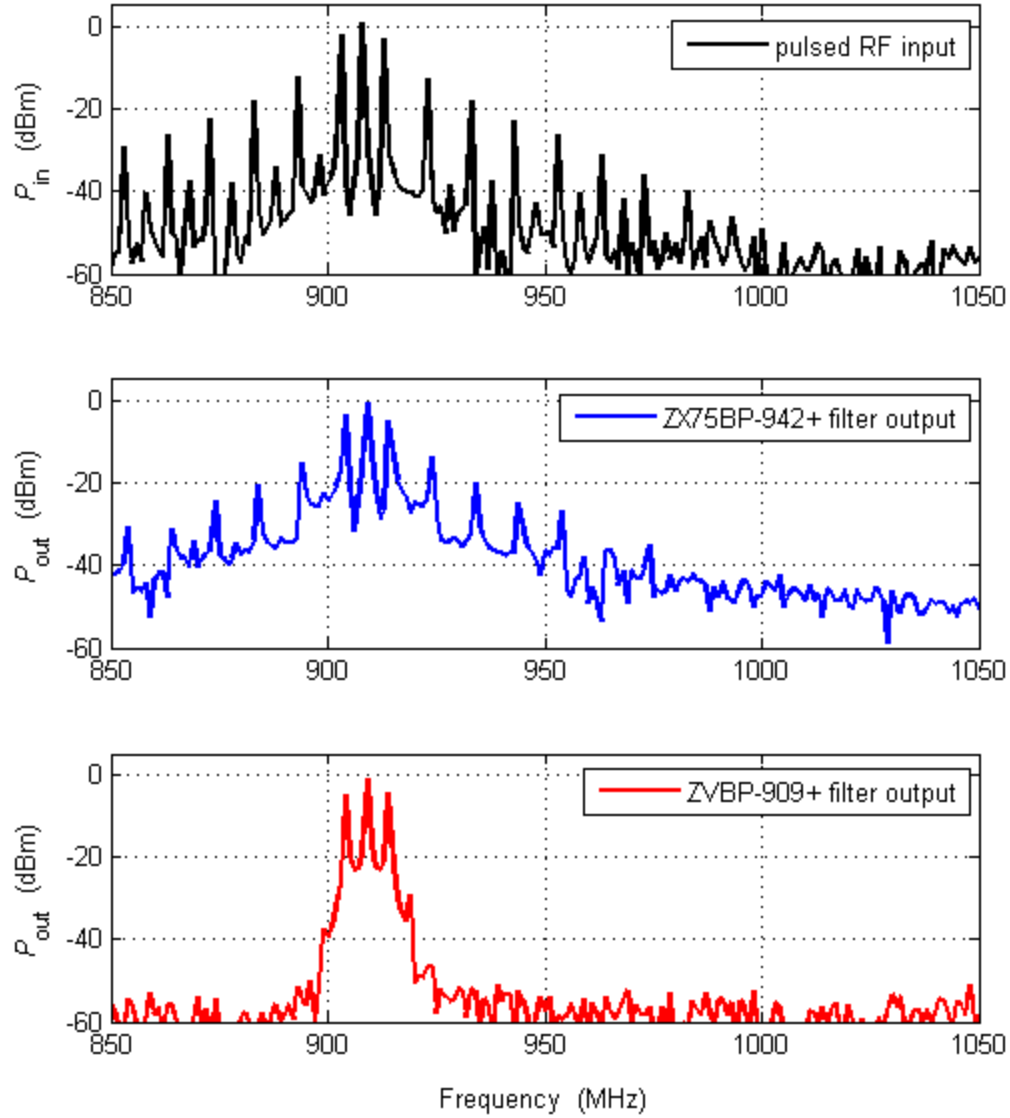
Fig. 3   **Switch-and-filter experiment: frequency-domain data for f_0 = 908 MHz and f_s = 5 MHz**

Figure 4 shows v_{in} and v_{out} for f_s = 10 MHz, and Fig. 5 shows the corresponding power spectra. Here, only 3 Fourier components are visible at the output of the ZVBP-909. Thus the time-domain waveform more closely resembles a single-frequency sinusoid. Significant amplitude modulation of the sinusoid is still evident, however.
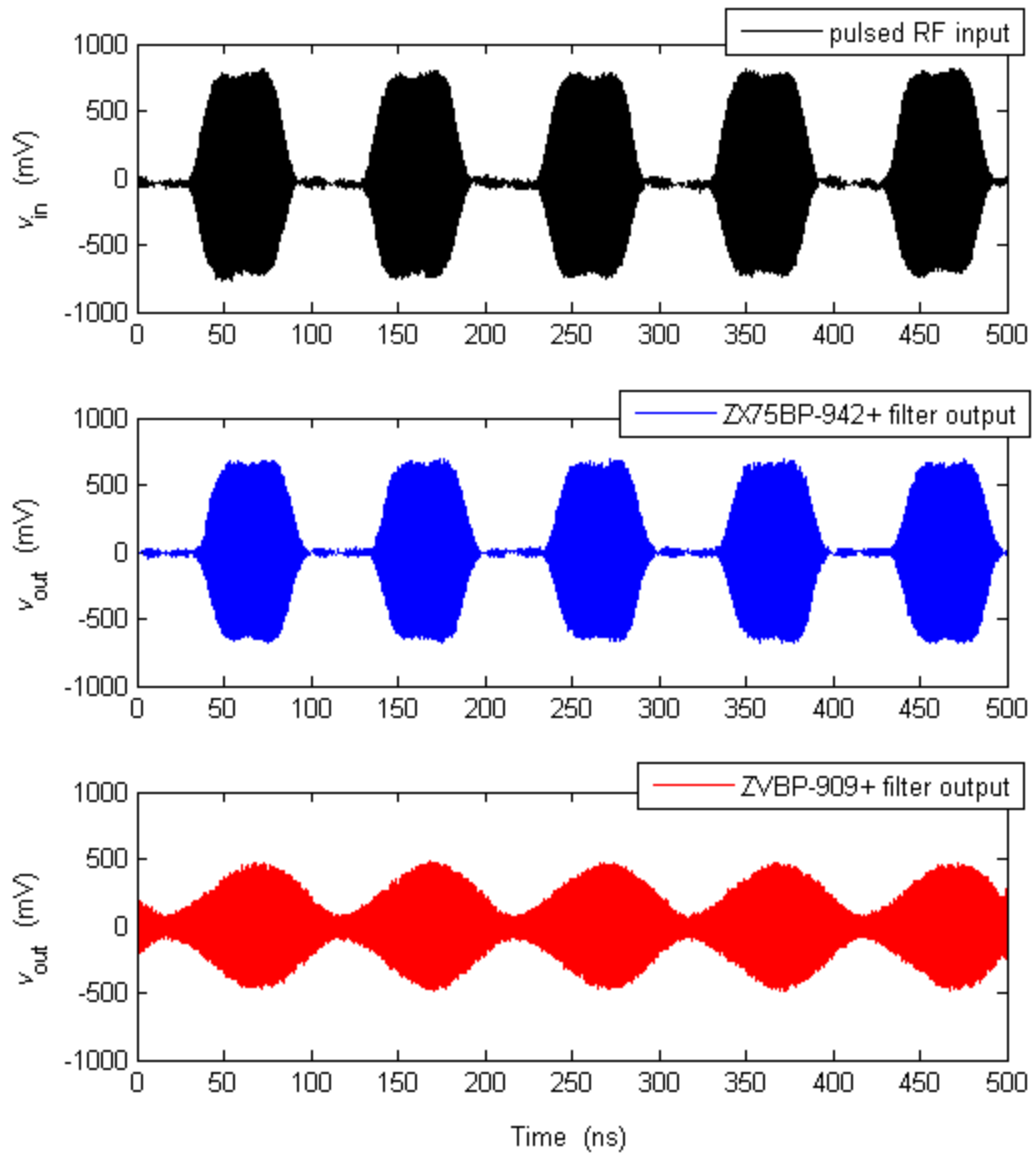
Fig. 4 **Switch-and-filter experiment: time-domain data for $f_0 = 908$ MHz, $f_s = 10$ MHz. The output of the ZX75BP-942 filter is essentially the same as the RF pulse input. The output of the ZVBP-909 filter contains less amplitude modulation compared to $f_s = 5$ MHz.**
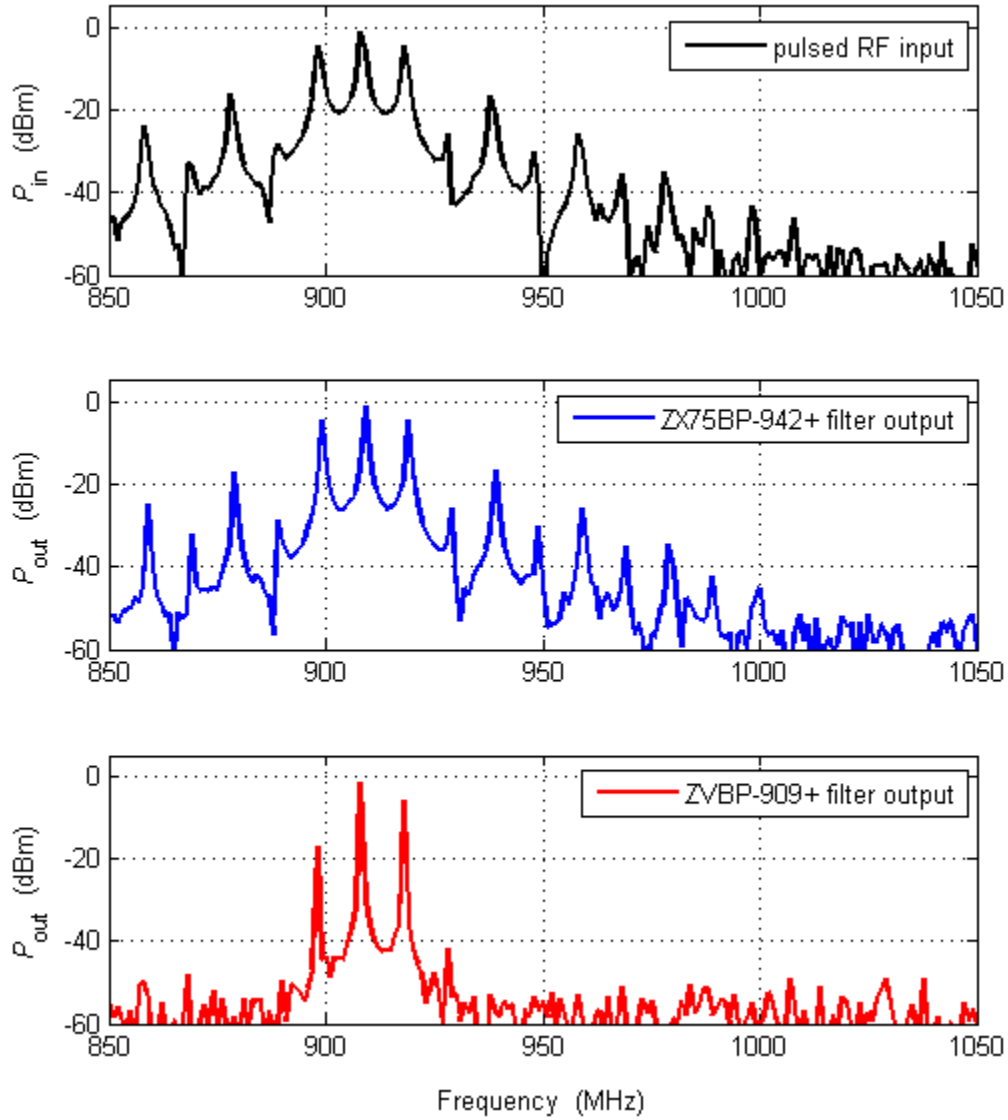
Fig. 5   **Switch-and-filter experiment: frequency-domain data for f_0 = 908 MHz and f_s = 10 MHz**

Figure 6 shows v_{in} and v_{out} for f_s = 20 MHz, and Fig. 7 shows the corresponding power spectra. At this switching frequency, only a single Fourier component at 908 MHz is observable at the output of the ZVBP-909 filter, and correspondingly the time-domain waveform is a constant-amplitude, continuous sinusoid. For this particular filter, this particular switching frequency, and this particular carrier frequency, the original RF pulse waveform has been converted to a continuous sinusoid. The experiment is judged successful, and this combination of filter and frequencies will be used as the starting point for the next phase of this research, which is to apply the switching-and-filtering LITMUS technique to intermodulation radar.

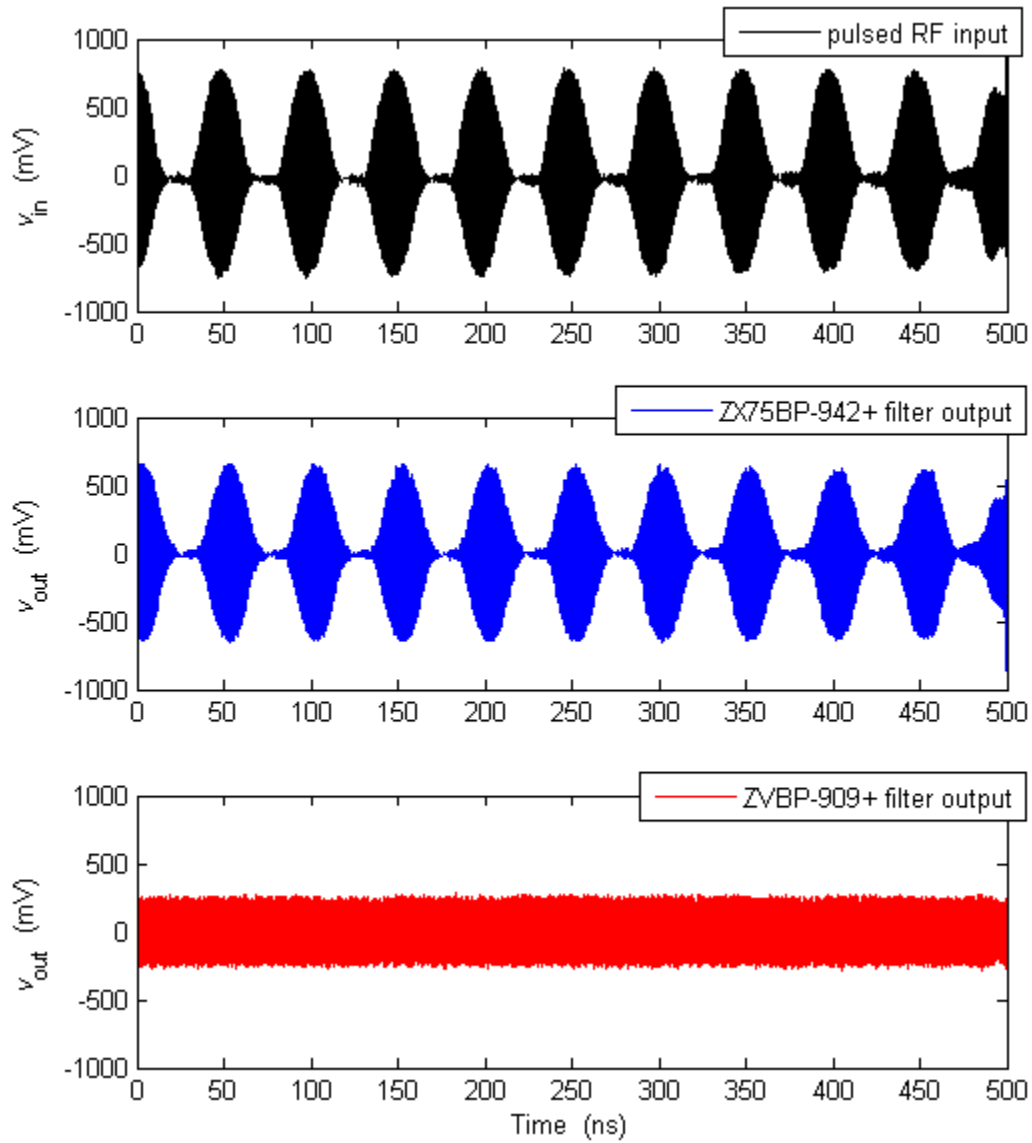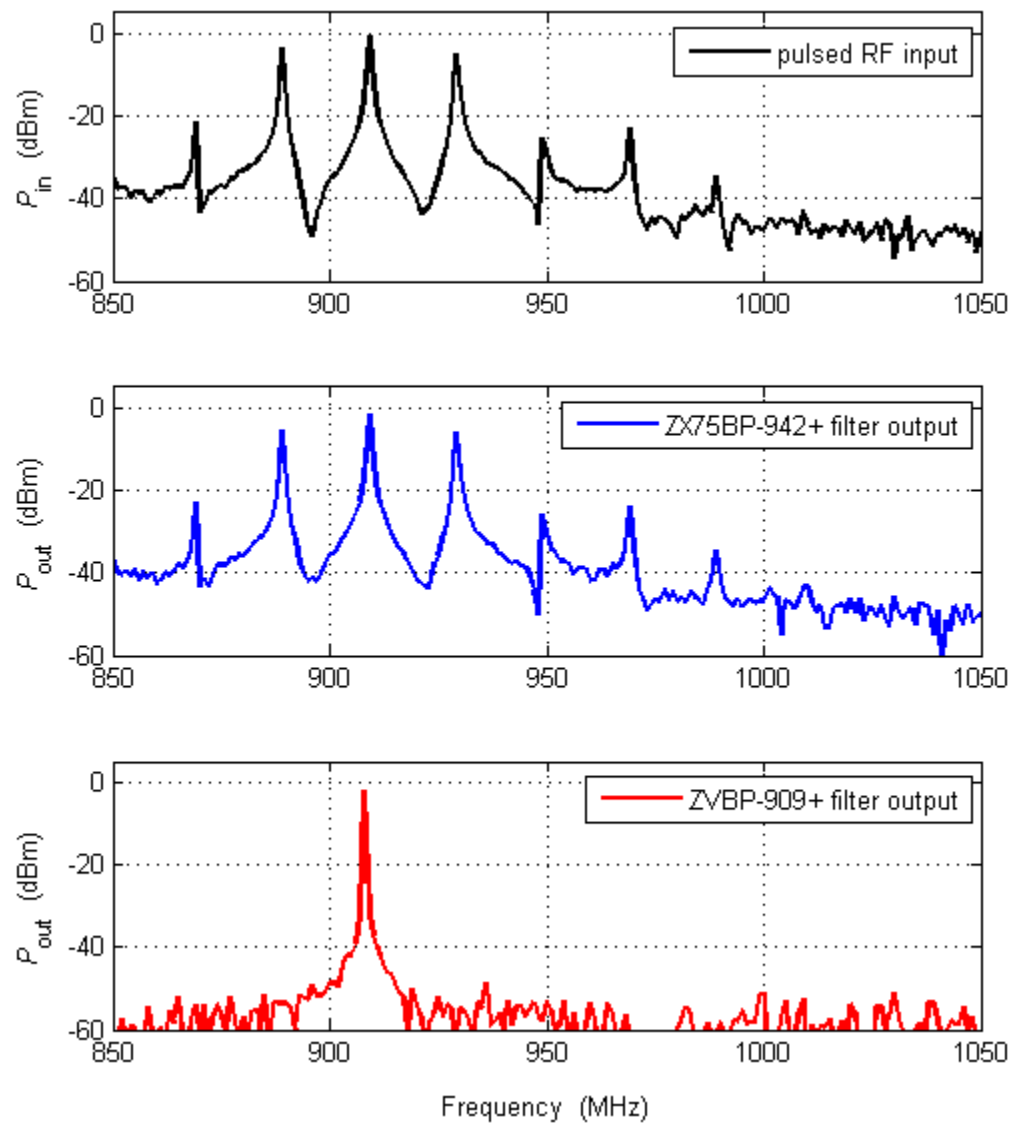**Fig. 6   Switch-and-filter experiment: time-domain data for f_0 = 908 MHz, f_s = 20 MHz. The output of the ZX75BP-942 filter is essentially the same as the RF pulse input. The output of the ZVBP-909 filter is a constant-amplitude, continuous sinusoid.**

Fig. 7   Switch-and-filter experiment: frequency-domain data for f_0 = 908 MHz and f_s = 20 MHz

3.   Conclusions

An experiment was performed to select a time-multiplexing rate and filter appropriate to apply LITMUS to intermodulation radar. The parameters tested were the following: a) carrier frequencies in the vicinity of 900 MHz, b) switching rates up to 20 MHz, and c) filters with passbands in the vicinity of 900 MHz. A test that successfully converted a single-frequency square-pulse train into a constant-amplitude and continuous-wave sinusoid was conducted at a carrier frequency of 908 MHz, a switching frequency of 20 MHz, and a bandpass filter centered at 909 MHz with a passband of 13 MHz. These parameters will guide the development of a follow-on experiment to detect nonlinear targets using a multitone probe with linearity improved by LITMUS.

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Appendix. Network Parameters

The network parameters S_{11} and S_{21} for the MiniCircuits ZX75BP-942+ and MiniCircuits ZVBP-909+ filters were recorded using the Keysight N5242A nonlinear network analyzer. The magnitude (in decibels) of each 2-port parameter is shown in Fig. A-1.
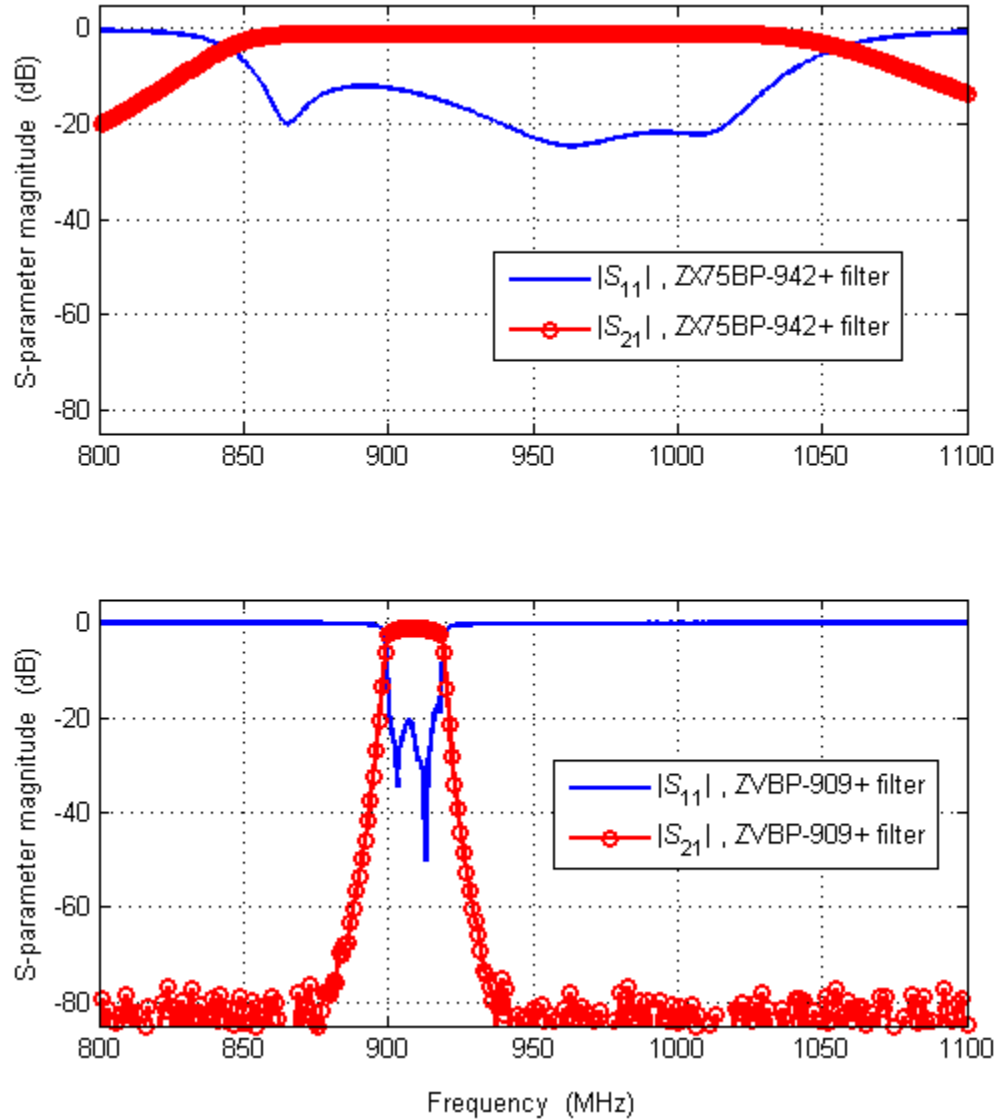
Fig. A-1 Two-port network parameters for the MiniCircuits filters used in this experiment. S_{11} and S_{21} were measured using the Keysight N5242A with 0-dBm output from Port 1.

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